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THE STUDY OF THE RELATIONSHIP BETWEEN CRACKS AND SEISMIC PARAMETERS OF ROCKS

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ABSTRACT

This paper presents the relation between main crack systems and physical properties of carbonate rocks. The existence of cracks in a rock mass causes the reduction of seismic wave velocity, which is smaller in direction perpendicular to a crack plane than in direction parallel to it. This affects the occurrence of the anisotropy of seismic wave velocity, which is characteristic for rocks with preferred orientation of cracks. The existence of relationship between crack and seismic anisotropy allowed to use geophysical methods for determination of fracture density and orientation of crack systems.

The research area is located in the south-east part of the Upper Silesian Trough. Tectonic observation and geophysical measurements was carried on the carbonate sequence on the both fold limbs building the Chrzanow-Wilkoszyn Syncline, originated during the Early Cimmerian movements, in the Upper Triassic – Middle Jurassic period. It was measured seismic waves velocity in the surface layers of rock mass and the strike azimuth and dip angle of cracks.The seismic anisotropy of the rock mass was done along radial profiles having common central point using P.A.S.I. Seismograph (Mod.16S24-N). Results of field measurements were interpreted to estimate components of crack and velocity tensors. Obtained outcomes allowed to compare the existing main crack systems on the both fold limbs with seismic measurements. Eventually we have shown that seismic measurements are useful tool to study the cracks anisotropy in rocks inaccessible for direct observations.

KEYWORDS: seismic measurement, crack tensor, velocity tensor

1. INTRODUCTION

One of the most characteristic features of rocks is occurrence of different kinds and size cracks. This surface discontinuities have an important influence on rocks physical properties. Elastic and electrical properties of rocks depend on size, density and orientation of crack as well as on amount and kind of medium which fill the fractures. Frequently, cracks are not randomly distributed in rock but they make one or more oriented sets. It causes anisotropy of physical properties especially anisotropy of seismic wave velocity. The existence of relationship between crack and seismic anisotropy allowed to use seismic methods for determining orientation of fracture systems and the crack density in sites where the rocks are inaccessible to direct observation.

Study area is located in the Wilkoszyn Syncline in the south-east part of the Upper Silesia Basin (Fig. 1). This syncline is a part of the Bytom-Brodła Syncline Zone, originated on the base of the older Paleozoic tectonic structure (Kurek et al., 1977) during the Early Cimmerian movements, in the Upper Triassic – Middle Jurassic period. In the Upper Carboniferous period mentioned zone had NW-SE axis direction to the west and WNW-ESE axis direction to the east. Recent NW-NE axis direction of the Wilkoszyn syncline results from the Alpine movements.

The carbonates formation of the Middle Triassic series developed in the eastern marginal part of the Permo-Triassic basin, usually known as German basin, consists of dolomites, limestones and marls (Fig. 2.).

Thickness of the Triassic sequence ranges from about 1 m to 200 m. Direct basement of the Triassic rocks is the coal-bearing clastic formation of Upper Carboniferous age, up to several thousand meter thick. The Triassic layers (the Keuper and the Rhaetian) consist of mudstones and claystones with dolomite, limestones and sandstones. The Lower Muschelkalk (Gorazdze, Terebratula and Karchowice Beds) carbonate rocks include so-called ore-bearing dolomites. According to Leach et al. (1996), the ore-bearing dolomites developed due to epigenetic alternation of limestones and early diagenetic dolostones. The contact of the ore-bearing dolomites with surrounded carbonate rocks may be complex, usually it is impossible to find sharp boundary between them. The Triassic rock series are covered by Middle and Upper Jurassic beds and next overlaid by Tertiary and Quaternary clastic sediments.

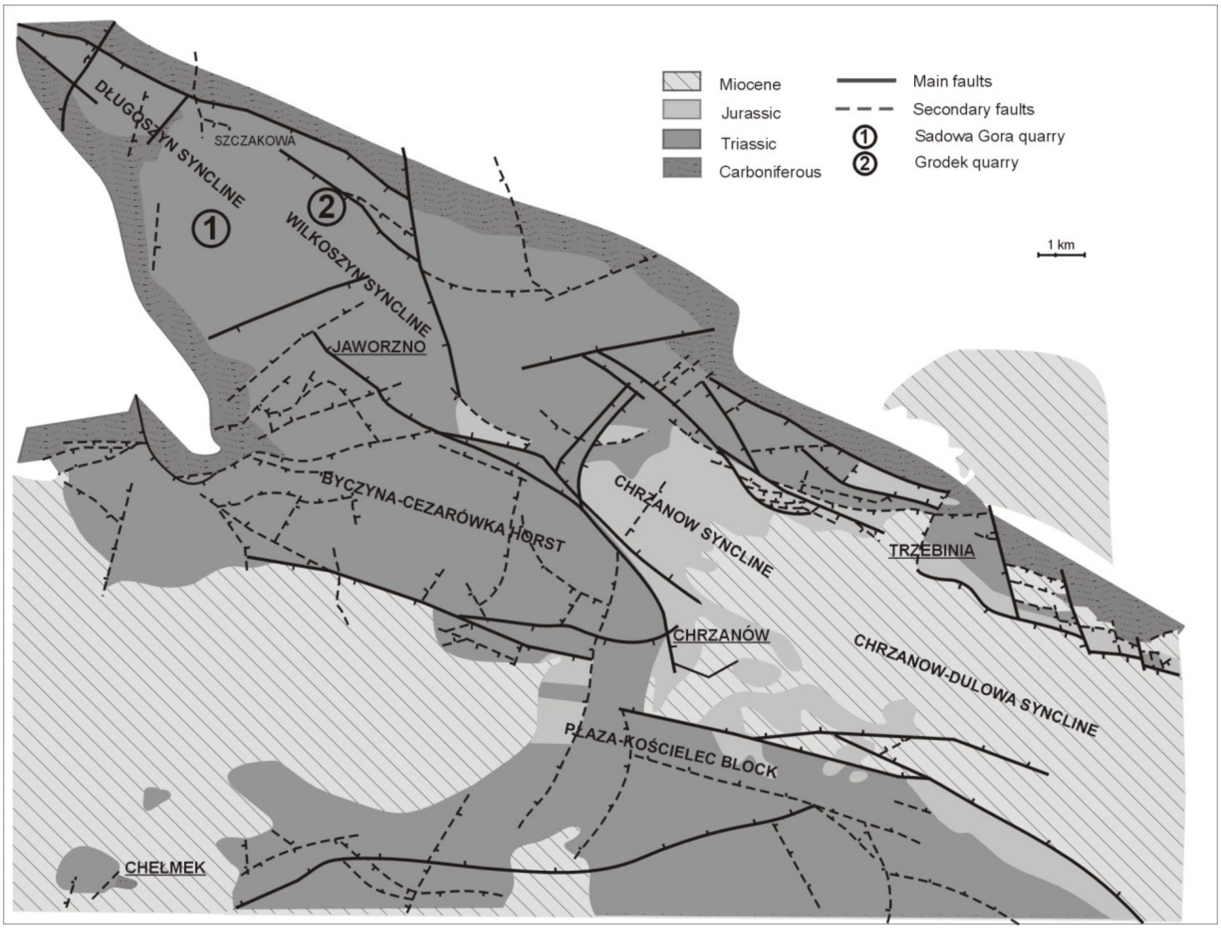

Fig. 1 Geological situation of the study area, without Quaternary sediments (after Kurek et al., 1977).

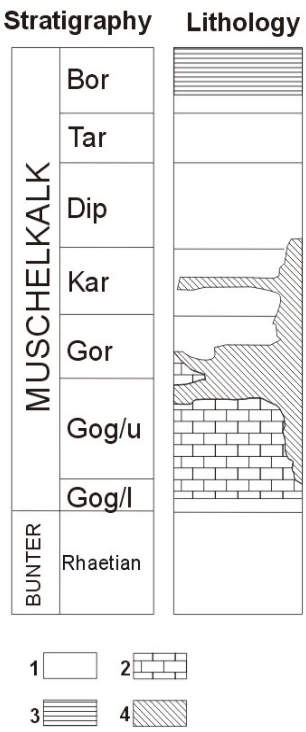

Fig. 2 Lithostratigraphy in the surroundings of the Wilkoszyn Syncline (after Szuwarzyński, 1996, modified).
1 – "primary" dolomites, 2 – limestones and marls, 3 – argillites and sandstones, 4 – epigenetic ore bearing dolomites, lithostratigraphic units: Gog/l – Lower Gogolin Beds, Gog/u – Upper Gogolin Beds, Gor – Gorazdze Beds, Kar – Terebratula and Karchowice Beds, Dip – Diplopora Dolomite, Tar – Tarnowice Beds, Bor – Boruszowice Beds.

The Wilkoszyn Syncline has been selected to present study because it gives the opportunity to make study on the carbonate rocks of the Gogolin Beds, the Lower Mushelkalk series (Fig. 2.) exposed in two closed quarries on the both sides of the syncline. On the south-west limb there is the "Sadowa Gora" quarry, which was exploited for limestone and marls. This pit is characterized by limestones, marls, cellular limestones, interbed limestone conglomerates, undulated limestones and ore-bearing dolomites in the roof part, which are visible on the practically vertical quarry walls. The "Grodek" dolomite quarry is located on the opposite - the north-east - limb of the Wilkoszyn Syncline. It was developed in the ore-bearing dolomites. Observed difference between lithological content of this two profiles results from the Triassic layers bedding, which gets 2^0–10^0 on the SW side of syncline and 8^0–20^0 on the NE side.

2. CRACK TENSOR AND VELOCITY TENSOR

Studying the relationship between seismic anisotropy and crack anisotropy in limestone and dolomite, we were only interested in fractures perpendicular to the bedding. This allowed us to calculate the two dimensional crack tensor and velocity tensors in a plane parallel to the layer surface (Oda 1982, 1984; Oda et al., 1984; Idziak, 1992; Stan and Idziak, 2005; Stan-Kleczek, 2008). The velocity tensor describes the anisotropy of seismic wave velocity. It expresses directional dependence of squared velocity which is related to the elastic modulus of medium. To make the tensor components non-dimensional measured velocity should be normalized by factor v_0, for example wave velocity in unfractured sample of the medium. Tensor of seismic anisotropy of the rank "k" (k= 0, 2, 4, ...) is a symmetrical tensor describing directional changes of $(v/v_0)^2$. For given velocity tensor of rank "k", the normalized squared velocity in direction "r" can be approximated:

$$\left(\frac{v}{v_0}\right)^2_{\vec{r}} = V_{l_1 l_2 l_3 \dots l_k} r_{l_1} r_{l_2} r_{l_3} \dots r_{l_k}$$

where:

$V_{l_1 l_2 l_3 \dots l_k}$ - components of the tensor of rank "k",

r_i - directional cosine of unit vector $r = (r_1, r_2, r_3)$ parallel to chosen direction "r". In the formula, Einstein's summation convention is used.

In a rock mass the tensor components can be determined from the set of N equations:

$$\left(\frac{v^{(h)}}{v_0}\right)^2_{\vec{r}} = V_{l_1 l_2 l_3 \dots l_k} r^{(h)}_{l_1} r^{(h)}_{l2} r^{(h)}_{l_3} \dots r^{(h)}_{l_k}$$

$l_1.l_2 \dots l_k = 1,2,3 \quad h = 1,2...N \quad N>k$

obtained for velocity measurements in N independent directions.

The crack tensor describes fracturing of the rock mass with definite orientation of cracks. It takes into account both geometry and orientation of cracks. The zero-rank crack tensor describes the density of cracks independently of their direction. The second-rank crack tensor is the first approximation to anisotropy description. In a three-dimensional case, the crack tensor is represented as a vector normal to the crack plane, but in a two-dimensional case it is presented as a vector normal to the crack trace. To describe crack anisotropy a tensor quantity called “crack tensor” can be used (Idziak and Stan-Kleczek, 2006).The crack tensor of rank “k” can be defined as:

$$\hat{F}_{ij \dots l} = \left\langle E A_{ij \dots l} \right\rangle,$$

$A_{ij \dots l}$ is cartesian product of the unit vector normal $\vec{n}$ to a principal plane of crack. To estimate the crack tensor components one has to know a statistical distribution of crack geometry and orientation, represented by density function E(a,c, $\vec{n}$) where “a” is diameter of crack and “c” is its aperture. The function should be symmetric in relation to $\vec{n}$:

$$E(a,c,\vec{n}) = E(a,c,-\vec{n}).$$

Estimators of the crack tensor components for penny-shape cracks can be calculated from the relation:

$$\hat{F}_{i,j \dots l} = \frac{\pi}{4} \int_0^{a^{\max}} \int_0^{c_{\max}} \int_\Omega a^2 c n_i n_j \dots n_l E(a,c,\vec{n}) da\, dc\, d\Omega,$$

where Ω - is the solid angle corresponding to the entire surface of the unit sphere.

The constitutive equation of fractured carbonate rock mass (Idziak, 1992) allowed to establish theoretical relationship between eigenvectors of crack and velocity tensors. The axes of velocity tensor should be rotated by 90º in relation to the axes of crack tensor.

3. EXPERIMENTAL STUDY

The direct mezostructure observations and seismic measurements were made in two quarries located on the both fold limbs building the Wilkoszyn Syncline (deposit 1 – limestone in “Sadowa Gora” quarry and deposit 2 – dolomite in “Grodek” quarry). P.A.S.I. seismograph was used for recording of seismic waves in the surface layers of rock mass. The measurements were made along precisely oriented radial seismic profiles. The azimuth interval between profiles was 10°. The seismic data were digitally recorded with up to 12 geophones at 3-meter spacing, so the profiles were 33-meter long. Seismic waves were generated by an eight kilogram hammer which was hit against a metal plate. The accuracy of seismic velocity measurement depends on the precision of apparatus and local wave velocity changes along the profile. The first break times of P waves were read from recorded seismograms.

Wave velocities were calculated from a slope of linear refraction travel time-offset relation obtained by least-squares fitting to experimental data. This also defined their standard deviation and variation coefficient (Table 1). The variation coefficient of P-wave velocity for deposits 1 and 2 is from 11 to 16 %. This relatively large value is caused by anisotropy. If the anisotropy is considerable, then the variation coefficient is greater.

The strike azimuth and dip angle of fractures were measured with a geological compass. There were measured 37 cracks in the “Sadowa Gora” quarry and 34 in the “Grodek” quarry. The small number of measurements is due to difficult

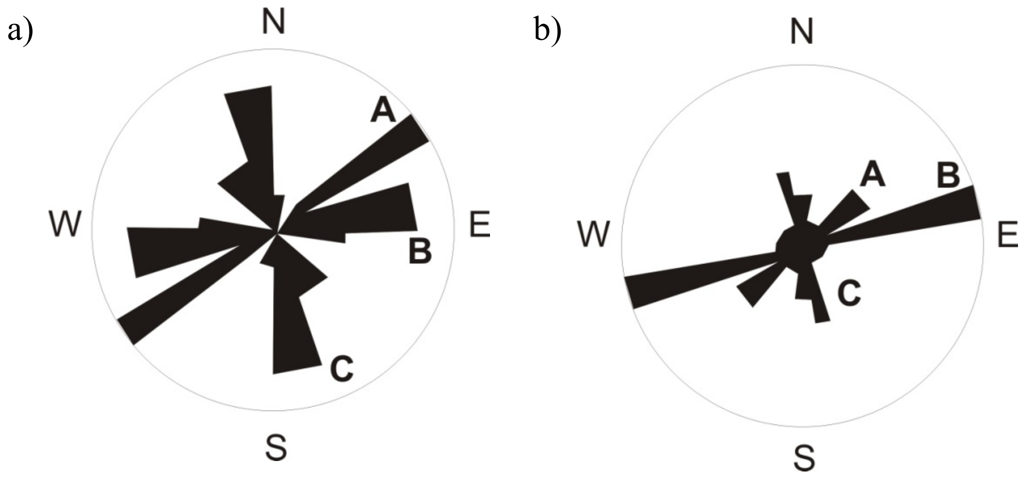

Fig. 3 The rose diagrams of cracks orientation with 10º counting intervals: (a) deposit 1, (b) deposit 2.

Table 1 Standard deviation and variation coefficient of *P*-wave velocity.

Investigated area	Standard deviation	Variation coefifcient
	P wave [m/s]	*P wave* [%]
deposit 1	115	11
deposit 2	545	16

accessibility to the practically vertical quarry walls. The rose diagrams were drawn on the basis of crack orientation data (Fig. 3).

Fractures identified in both pits were vertical or sub-vertical. Three main crack systems, with the same number of cracks, were recognized in the "Sadowa Gora" quarry (deposit 1): $50^0 – 60^0$ (A), $70^0 – 90^0$ (B) and $160^0 – 180^0$ (C). The similar strike azimuth orientation were observed in the "Grodek" quarry (deposit 2), but the main crack systems have different number of cracks. The strike azimuth of $70^0 – 90^0$ (B) has appeared more often than others direction.

In investigated deposits, azimuth distributions of seismic wave velocity are characterized by the occurrence of velocity maxima at specific directions. These directions agree with the measured directions of main crack systems (Fig. 4).

4. RESULTS AND INTERPRETATION

The model of crack medium predicts that the axes of velocity tensor should be rotated by 90° in the relation to the axes of crack tensor, neglecting nonlinear effects connected with the propagation of wave in a crack medium (Idziak, 1992). The obtained *P*- wave velocity data were used for calculating the velocity tensors. On the basis of theoretical dependence, reading the azimuth of velocity tensor we can assess the azimuth of crack tensor. The measurements of crack systems orientation and their geometrical parameters were used to calculate the crack tensor. It allowed to compare results with theoretical dependence (Table 2, Fig. 5). Differences (about 10°) can be caused by nonlinear effects, such as the measurement accuracy, or imprecise assignment of profile azimuth and imprecise interpretation of the first break times of *P* waves (about 0.5 ms). The crack orientation measurements can be important for the error assessment. The differences can be about 2 %. In case of deposit 1, the major axis of velocity tensor is rotated about 90° in relation to the major axis of crack tensor. For deposit 2, relation could not be observed because in this case there are three nearly parallel crack systems so the second-rank crack tensor and velocity tensor are a resultant for these crack systems.

The crack tensor of rank four is also a resultant for these crack systems. For nearly parallel crack systems, the distribution function is symmetrical in relation to characteristic axes. One of these axes shows the resultant direction for both crack systems and the second is perpendicular to it.

Table 2 The comparison of second-rank crack tensor with second-rank velocity tensor for the studied deposits.

Investigated area	Azimuth of velocity tensor axis		Azimuth of crack tensor axis	
	major	minor	major	minor
deposit 1	1	91	76	166
deposit 2	82	172	53	143

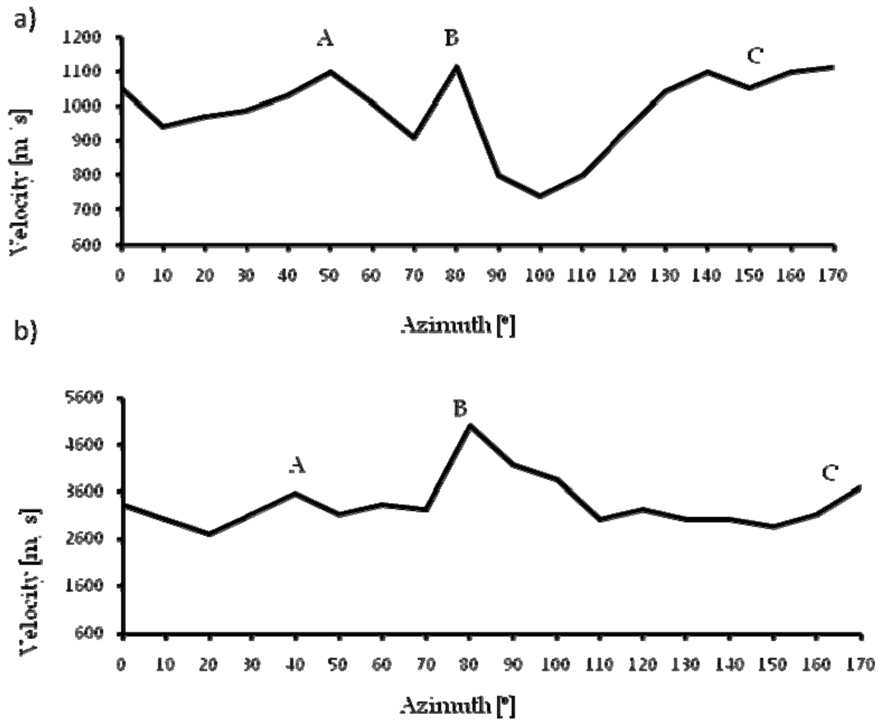

Fig. 4 Comparison of azimuth of P- wave velocity and crack systems a) deposit 1, b) deposit 2.

5. CONCLUSION

In consequence of geological observation and seismic studies carried on both fold limbs building the Wilkoszyn Syncline we have got a confirmation that the main directions of cracks in carbonate rocks (limestone and dolomite) are consistent with the maxima of velocity. Anisotropy of seismic wave velocity is reflected in the major systems of cracks. Tensor calculus provides an additional tool to study the relationship between crack anisotropy and seismic anisotropy and thus the connection between main crack systems and maxima of velocity.This is in accordance with the earlier study of Idziak (1992), Stan and Idziak (2005) and Stan-Kleczek (2008), which have showed that seismic methods are most suitable for different rocks. Second rank velocity tensor determines the general characteristics of the elastic anisotropy of rock massive. Fourth rank velocity tensor plays an important role during the study of fracturing using seismic methods because it allows for more precise information on schedules cracks, complementing the general characteristics of the anisotropy of the massive.

If the fracture systems intersect at an angle about 45 degrees, the directions of the main axis of the velocity tensor are perpendicular to the main directions of crack tensor. This situation has a place in the case of deposit 1 – "Sadowa Gora" limestone quarry. It can be observed that the velocity tensors of rank four delivered more information about the crack distribution. When crack systems are nearly parallel, the velocity tensor of second and fourth rank is a resultant of all crack systems, so in this case the seismic interpretation is more difficult than for perpendicular crack systems and appointment of anisotropy for individual crack systems is ambiguous (deposit 2).

The quarry walls on the study area are practically vertical, it cause difficulties in doing the direct geological observation. The geophysical measurements are seems to be the best tools for indirect cracks study.

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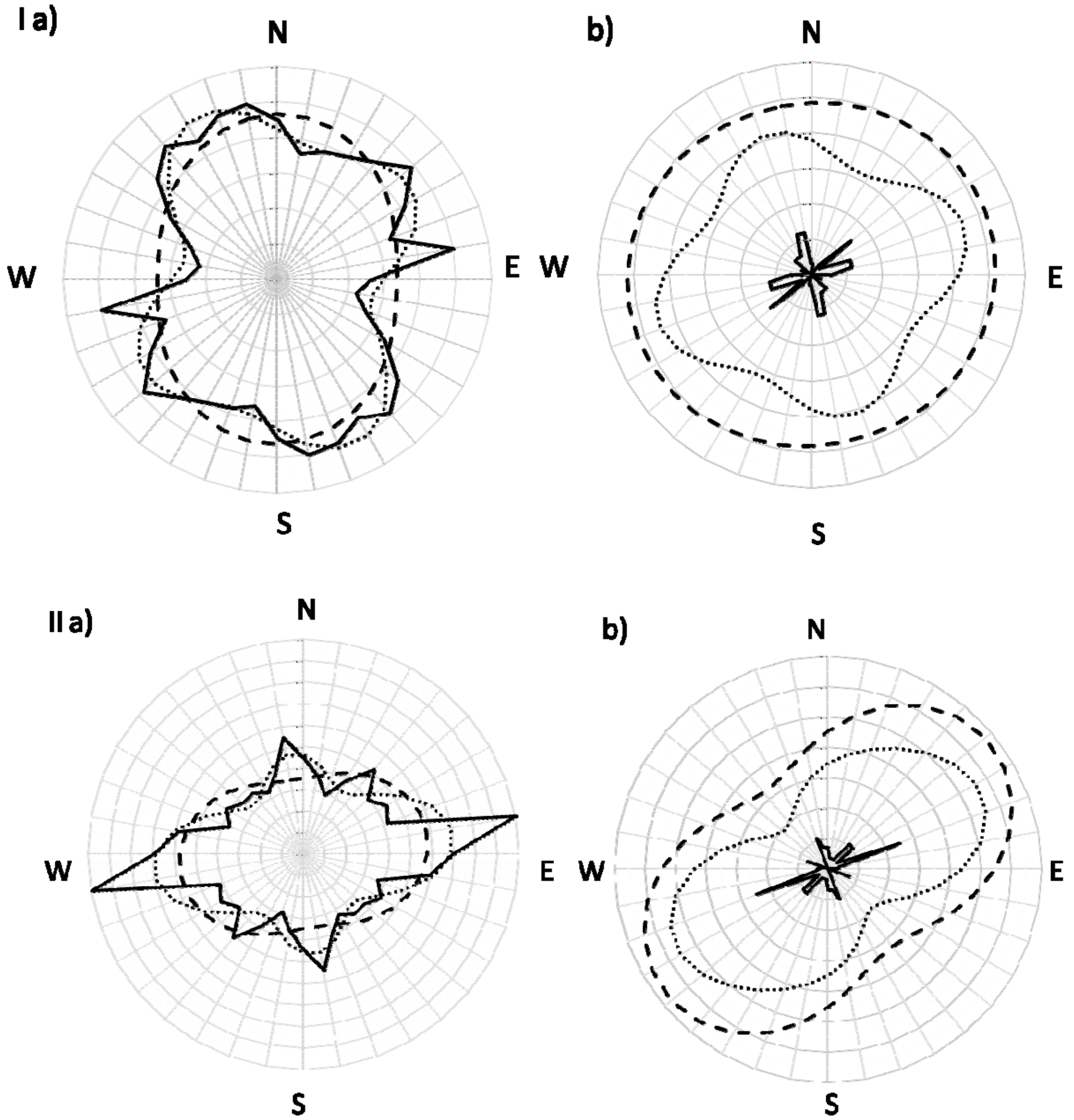

Fig. 5 The comparison between the crack tensor and the velocity tensor: I - deposit 1, II - deposit 2. Relationships between the azimuth of seismic profile and P-wave (panels a) squared velocity (solid line), velocity distribution based on the tensor of rank two (dashed line), and the tensor of rank four (dotted line). Panels b present spatial distributions of cracks orientation based on rose diagrams (solid line), the tensor of rank two (dashed line), and the tensor of rank four (dotted line).

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